Penetration of the Ionosphere by Very-Low-Frequency Radio Signals—Interim Results of the LOFTI I Experiment*

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Summary—LOFTI I is the first of a series of Navy satellite experiments designed for determination of the degree and extent of very-low-frequency (VLF) radio wave penetration of the ionosphere. This investigation has provided unique data on intensity, time delay, echoes, and other characteristics of VLF signals received in the ionosphere from transmitters on the Earth's surface.

Theoretical studies carried on concurrently with planning and implementation of the experiment have indicated that VLF radio energy from transmitters operating below the lower atmosphere-ionosphere interface should appear in the ionosphere in useful amount. The LOFTI I telemetry records show relatively strong signals in the ionosphere from 18-kc transmitters on the terrestrial surface. The signals were attenuated less at night and appeared as far away as Australia, 10,000 miles from the transmitter.

Statistical treatment of the data so far reduced shows that the attenuation of magnetic field intensity of the 18-kc time pulses from Naval Radio Station NBA, as measured near extreme line of sight distances to the north of the station, was less than 13 db 50 per cent of the time at night and less than 38 db 50 per cent of the time during the daylight hours. The data studied so far shows very little effect of altitude on signal intensity, an observation which agrees with the theoretical treatment based on a model ionosphere.

The observed time delays of the 18-kc signals range from 10 to 200 msec, indicating that VLF propagation velocity in the ionosphere is much lower than in free space. The occurrence of whistler-path propagation is indicated by sequential echoes of the NBA time pulses which appear in the telemetry records as much as 4/3 seconds after the directly-received pulses.

Much data remains to be reduced from LOFTI I. Further experiments are planned to provide data on electric dipole impedance in the ionosphere (lost to the LOFTI I experiment because of a launch vehicle malfunction), on the effect of operation at higher latitudes and over a wide range of signal frequency, and on the characteristics of the signals produced in the lower atmosphere by VLF transmitters radiating in the ionosphere.

INTRODUCTION

LOFTI (LOw Frequency Trans-Ionospheric) I is the first of a series of Navy satellite experiments designed to explore low-frequency radio wave propagation in the ionosphere. The LOFTI studies were proposed early in 1958 by the Naval Research Laboratory as part of a comprehensive satellite communication research program.

The LOFTI I experiment was planned as an initial study of the magnitude and other characteristics of VLF radio signals emitted at the earth's surface as observed in the ionized regions of the atmosphere. Sufficient definitive data was expected to guide the planning of further LOFTI experiments, which would add to the fund of scientific information and lead to improved communication systems.

GENERAL NATURE OF THE IONOSPHERE

Earth's ionosphere impedes the passage of low-frequency radio waves from the terrestrial surface into outer space. At the higher frequencies, its effectiveness as a barrier decreases to a degree such that it becomes essentially negligible above, roughly, 100 Mc, so far as transmission loss is concerned.[1] The ionization of the atmosphere, which is caused largely by solar radiation, varies above any particular point on the earth's surface with time of day, season of the year, solar storms, the sunspot cycle, etc. The observed influence of the ionosphere on terrestrial radio wave propagation has led to its classification into strata, the D region and E, F_1 and F_2 layers which, when all are present, appear in ascending order above the Earth from about 50 to about 400 km (roughly, 30 to 250 statute miles) altitude.

Somewhat more than half of the Earth's rotating atmosphere always faces the sun and is subjected to the intense and variable solar radiation while the rest is in shadow. The depth of atmosphere through which the sun's rays must pass becomes greater toward the periphery of the illuminated hemisphere. A major change of atmospheric ionization occurs in the transition from sunlight to shadow and vice versa, resulting in significant diurnal variations in the performance of terrestrial radio systems operating below approximately 100 Mc. Fig. 1 illustrates one effect of the daily cycle.[2] It shows the change in phase delay of a VLF signal originating about 3200 km (2000 miles) due south of a receiver, as observed over a 24-hour period. The 18-kc transmitter at Naval Radio Station NBA, Canal Zone (which was the main source of VLF signals in the LOFTI I experiment) radiated the signals observed in the Fig. 1 measurements. The measuring receiver was located at the

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* Received by the IRE, April 10, 1961; revised manuscript received, October 13, 1961.

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[1] K. G. Budden, "Radio Waves in the Ionosphere" Cambridge University Press, London, Eng.; 1961.

[2] From A. R. Chi and H. F. Hastings of the Radio Division, USNRL.

Naval Research Laboratory in Washington, D. C. The transmitter and receiver sites passed through the sunlight to shadow zone and back almost simultaneously during the period in which these measurements were made (near the autumnal equinox). The increase in phase delay observed after sunset indicates lengthening of the signal path between the stations. Greater path length would be one result of the disappearance of the *D* region with the onset of darkness and the consequent increase in height of the earth-ionosphere space.

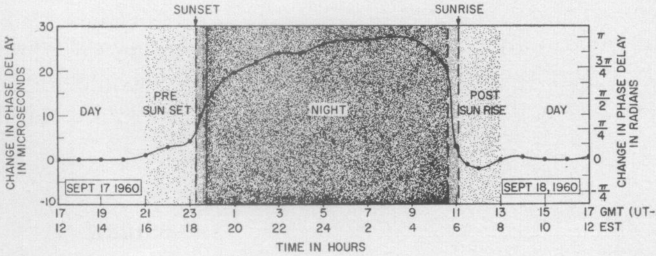

Fig. 1—Effect of diurnal change of solar illumination on the propagation time of an 18-kc radio signal. North-south path; distance between transmitter and receiver approximately 3200 km; both stations passing almost simultaneously from daylight into darkness and from darkness into daylight. Note rapid reduction of phase delay immediately preceding sunrise, indicating swift reconstitution of *D* region after a less rapid disappearance with the onset of darkness. (From Chi and Hastings, NRL.)

The data available indicates that the density of the atmosphere even at the lower boundary of the *D* region is very low, about 1×10^{-3} of the sea level value, and drops rapidly with increasing height. At 400 km (250 miles) altitude, atmospheric density apparently is near hard vacuum proportions, about 1×10^{-11} of the sea level atmosphere. The average rate of electron collision with other particles in the ionosphere (the collision frequency) decreases correspondingly, although it is also affected by other factors such as temperature and ion concentration.

Fig. 2 indicates degree of ionization in terms of free-electron concentration as a function of altitude above the earth's surface.[3,4] It also shows the general nature of the variation of collision frequency with altitude.[3]

Propagation Loss in the Earth-Ionosphere Circuit

The propagation loss between a VLF transmitter on the ground and a receiver within line-of-sight distance in the ionosphere involves three elements. One of these is the spreading loss in the lower atmosphere to the point of signal entry into the ionosphere. Additional circuit attenuation is then introduced as the result of splitting of the radio wave as it impinges on the boundary region or interface between the ionosphere and the lower atmosphere. Part of the signal energy is reflected back toward the Earth's surface and the remainder is propagated upward in a magneto-ionic mode toward outer space.

The further attenuation of the signal caused by absorption of energy as the radio wave traverses the ionized medium depends on wave frequency, inclination of the wave normal relative to the Earth's surface, the electron density, and the collision frequency. The last two factors are the ones most altitude dependent. Magneto-ionic theory indicates that VLF radio waves will propagate within the ionosphere with least absorption when the angle of inclination θ of the wave normal relative to the geomagnetic field is zero or 180°. Since the VLF wave front after entry into the ionosphere is not planar, some reduction in field intensity due to spreading as the wave moves upward may be expected.

The computed rate of attenuation of 18-kc signal level due to absorption within the model ionosphere of Fig. 2 (for the condition $\theta = 0$) is shown in Fig. 3 as a function of altitude above the terrestrial surface.

The attenuation rate is approximately

$$\alpha = 1.8 \times 10^{-8} N^{1/2} \nu, \tag{1}$$

in which α is attenuation in db/km, N is the number of free electrons per cubic cm and ν is the collision frequency in number of collisions per second. This expression is derived from a statement defining the complex refractive index of a magneto-ionic medium (Appendix I). The coefficient (1.8×10^{-8}) of (1) is valid only when the electron density is greater than 10^3 electrons per cubic cm, the collision frequency is less than 10^6 collisions per second, and the gyro frequency is approximately 1000 kc. These conditions hold generally for the LOFTI I experiment. The equation in Appendix I was used in calculating Fig. 3 to arrive at more exact values than provided by (1).

Fig. 4 (derived from Fig. 3) shows the cumulative least possible attenuation of an 18-kc signal traversing the ionosphere radially outward from Earth within the range of altitude covered by LOFTI I. This loss does not include whatever attenuation of signal level may result from spreading of the signal energy within the ionosphere and also does not include the interface or entrance loss previously mentioned. It appears that most of the absorption loss attributable to the ionosphere is accumulated in passing through the *D* region between about 60 and 130 km altitude (37 and 80 miles) and that there is little further attenuation with further increase in altitude. The calculated total attenuation caused by absorption in the model ionosphere in its midday state is less than 30 db (about 27 db) under the conditions here considered. The corresponding least possible loss in passing through the model night ionosphere is about 2 db.

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[3] J. A. Ratcliffe, "Physics of the Upper Atmosphere," Academic Press, New York, N. Y., and London, Eng.; 1960. See especially p. 108: summary graph of data for summer noon, middle latitudes, and sunspot minimum.

[4] Stanford Research Institute model of electron density in the night ionosphere.

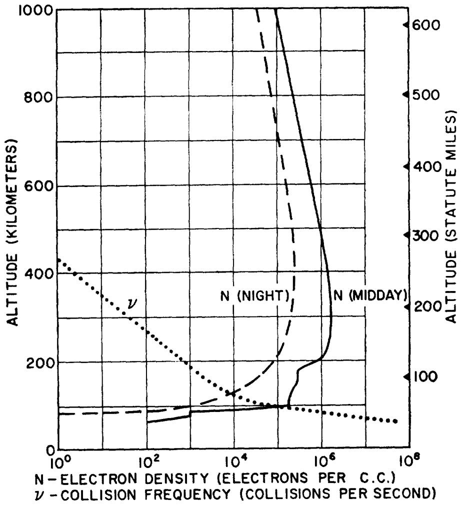

Fig. 2—Estimated concentration of electrons in the night and day atmosphere and electron collision frequency vs altitude. (After SRI and Ratcliffe.)

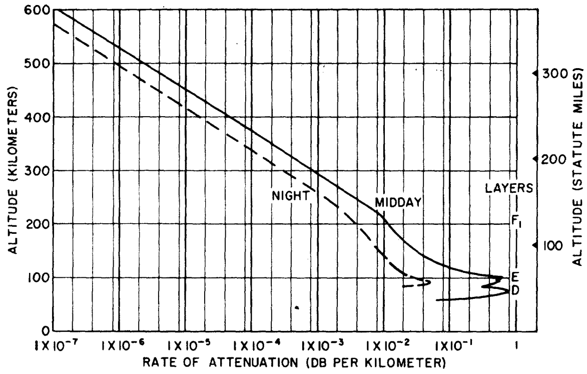

Fig. 3—Computed rate of attenuation of an 18-kc radio wave in the model ionosphere of Fig. 2 vs altitude.

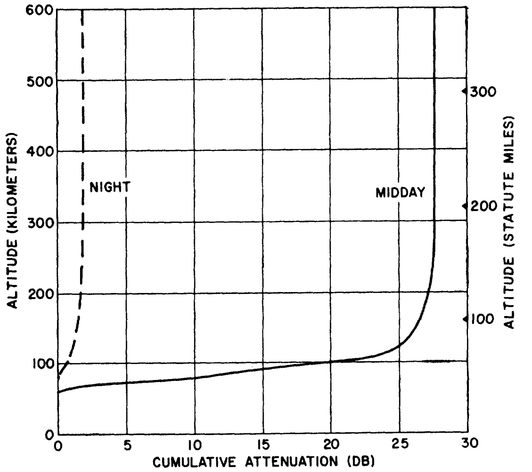

Fig. 4—Minimum possible transmission loss (least cumulative attenuation) of an 18-kc radio wave passing vertically upward through the model ionosphere of Fig. 2 vs altitude. Geomagnetic field aligned with direction of propagation. (Part of the signal energy that reaches the lower boundary of the ionosphere from the lower atmosphere does not penetrate the interface. The consequent reduction in signal level (the interface loss) and any spreading loss of the ionosphere are not included in the attenuation shown above.

SYSTEM CONCEPT OF THE EXPERIMENT

The LOFTI I experiment required three radio links, as shown in Fig. 5. Navy shore transmitting installations were the sources of VLF signal. Originally, it was planned that three mutually orthogonal magnetic dipoles (loop antennas) would be mounted on the satellite, each connected to an individual VLF receiver. In addition to measurement of VLF signal level, comparison of the signal output of the three loops in conjunction with satellite aspect data would provide indication of direction of wave arrival and other information. Another VLF receiver in the satellite, employing an electric dipole antenna (two whips) and a test oscillator periodically connected to the antenna, would indicate the effect of the ionosphere on electric antenna impedance and tuning. A similar test oscillator would be provided for the loop receivers.

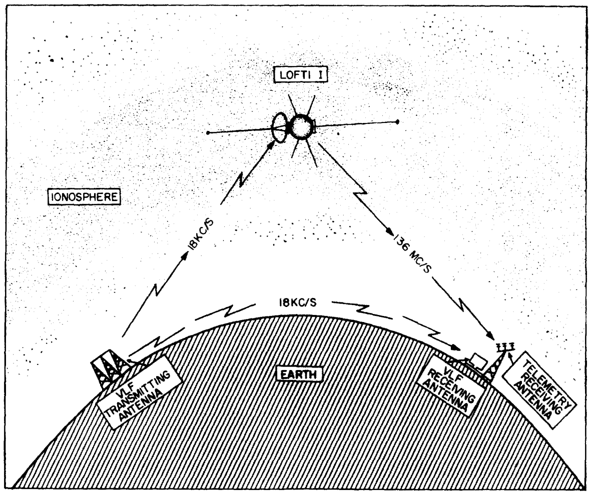

Fig. 5—System concept of the LOFTI I experiment showing the three basic radio links.

The various VLF signal outputs would each modulate the frequency of an assigned subcarrier of the satellite's VHF amplitude-modulated telemetry transmitter. The subcarriers of the VHF telemetry transmissions and terrestrial signals in the range of 0.3 to 30 kc received at the ground stations were to be recorded on magnetic tape together with other related data. The records would subsequently be reduced and analyzed to derive attenuation, amplitude distribution, group delay, phase delay, Doppler shift, noise in the ionosphere and other desired items of information.

IMPLEMENTATION OF THE EXPERIMENT

In the fall of 1959, it was found that additional payload could be accommodated in a forthcoming satellite launch (Navy's TRANSIT III B). Simultaneous launch of LOFTI I with TRANSIT would make it possible to proceed with the VLF study with least delay and expense. It was intended that the two satellites separate and go their individual ways when orbit had been attained. The inclination of the orbit (28°) and its constant height (about 1000 km or 600 statute miles) had been chosen for the TRANSIT experiment. Allowable payload considerations governed LOFTI satellite size and weight, and limited its VLF antenna complement to a single plane loop and a two-element whip. Two identical VLF receivers were coupled to the two antennas through suitable networks. Both receivers were tuned to 18 kc, the frequency of Naval Radio Station NBA's VLF transmissions.[5]

Station NBA is located in Panama (Canal Zone) at close to 9° north latitude, well inside the ±28 degree limits of the intended orbit. This station transmits highly precise time pulses on a very accurately controlled constant frequency carrier.[6] Radiated power is about 30 kw. The carrier frequency, nominally 18 kc, is very slightly offset to compensate for the difference between Universal Time (UT-2) and Atomic Time (A-1). These signals would be easily identifiable in the telemetry records and would in addition serve as a highly accurate time and frequency reference. Also, the periods between pulses would provide sequential intervals for determination of VLF noise level in the ionosphere.

ORBIT ATTAINED

The two-satellite combination was launched at 10:45 P.M. Eastern Standard Time (EST) on February 21, 1961 from Cape Canaveral, Florida, on a Thor/Able-Star rocket vehicle. Unfortunately, the second stage of the rocket did not separate from the satellite assembly. This malfunction interrupted the programmed sequence of events and prevented satellite separation. The three components (rocket and satellites) remained locked together, moving as a unit along an orbit with the intended apogee but a perigee so low that the life of the assembly turned out to be only about 36 days and 9 hours. LOFTI I made its last transmission on March 30, 1961.

The new composite satellite, designated 1961 ETA, had the following computed major orbital elements four days after launch:[7]

apogee—960 km (597 statute miles),
perigee—166 km (103 statute miles),
period for one revolution, perigee to perigee—95.9 minutes,
progression of perigee—+10.67 degrees per day.

By accident, LOFTI I had achieved an eccentric orbit which closely approached the ideal originally envisioned for this VLF experiment. It had begun a short career of plunging up and down through the upper reaches of the ionosphere 15 times each 24 hours, passing through the *F* layers and approaching the *E* layer about as closely as a satellite could without burning up immediately because of atmospheric friction.

LIMITATIONS ON THE EXPERIMENT

Other departures from the intended conditions of the experiment were not so desirable as the eccentric orbit or as acceptable as the shorter life expectancy of the satellite. It had been planned that the two 15-foot whip antennas wound on spools inside LOFTI I would be unreeled some time after satellite separation to function as a 30-foot electric dipole. LOFTI should then have been rotating about an axis parallel to the plane of its loop and perpendicular to a line drawn from the center of the loop to the center of the satellite's shell. Extension of the whips would have slowed this rotation to between 15 and 30 rpm. The resulting continuous slow spin (about 120°/sec) would have swept the loop and whip antennas through a maximum output position relative to the signal wave front twice each revolution of the satellite. Satellite attitude information would have been provided by the variations in earth and solar aspect sensor output.

The unseparated trio (rocket and satellites) did achieve a very slow tumbling and rotating motion (roughly, 1/20 rpm) which, however, was not a satisfactory substitute for the intended rotation. As a result, the aspect sensors scanned much too slowly to be effective. LOFTI's whip antennas could not be extended because of interlocks in the interrupted launch sequence and the physical presence of TRANSIT.

Another difficulty resulting from the failure to separate was that TRANSIT electronics interfered with VLF signal reception by LOFTI. The radio and electrical systems of both satellites had been designed on the premise of wide physical separation of the two systems in orbit. The desired signal data must consequently be separated not only from background noise but also from TRANSIT interference.

Thus, although all of LOFTI's instrumentation was operative and capable of performing as intended, only the loop receiving system could function at full inherent capability so far as VLF operation was concerned, and even it was misoriented and partially jammed by TRANSIT interference much of the time. NBA signals did appear in the output of the whip receiver during launch and also during night passes when the satellite came close to the transmitter, even though the whips remained within LOFTI's shell unextended. However, it is possible that the VLF energy was coupled into the whip receiver from the loop receiving system in some manner.

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[5] An experiment of similar configuration was proposed by Storey in 1959 for determination of local electron density by measurement of wave admittance in the ionosphere (L. R. O. Storey, "A method for measuring local electron density from an artificial satellite," *Res. NBS*, vol. 63D, pp. 325–340; November–December, 1959.)

[6] See U. S. Naval Observatory Time Service Notice No. 8; November 18, 1959. Time and frequency control is provided by the Observatory; control instrumentation was provided by the U. S. Naval Research Lab. in 1959.

[7] Orbital data from NASA; more complete tabulation in Appendix II.

Electric antenna detuning could not be observed because of inability to extend the whips. No significant change in magnitude of loop impedance appears in the data so far examined.

Portions of the Ionosphere Observed in the Experiment

During its 562 revolutions around Earth, LOFTI I and its companions traveled more than 14 million statute miles at an average velocity of approximately 4.7 miles per second. In its many traversals of the atmosphere, LOFTI moved within a belt roughly 4000 miles wide, 500 miles deep, 100 miles off the Earth's surface and centered above the equator.

Ten ground stations located in North and South America (indicated by small circles in Fig. 6) were instrumented to receive the 136.17 Mc telemetry signals radiated by LOFTI. The VLF transmitting stations which were the sources of 18-kc signals in the experiment appear in Fig. 6 as small stars. Three of the receiving stations were on an approximately east-west line and eight were approximately in line north and south along the meridian of station NBA. An eleventh station located in south-central Australia received the telemetry signals in that region.

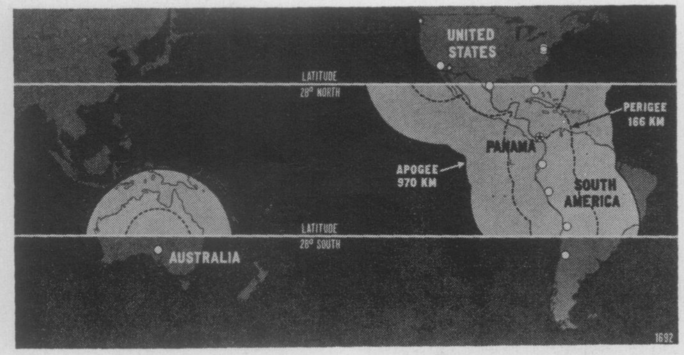

Fig. 6—Terrestrial areas over which VLF reception by the satellite (at highest apogee and lowest perigee altitude) could be observed by telemetry. Location of telemetry receiving stations is indicated by circles; sites of VLF transmitters involved in the experiment are indicated by stars.

The eleven stations could observe VLF signal reception by the satellite when it was over the territory shown lightly shaded in Fig. 6. These two regions were entirely covered by telemetry at highest apogee of the satellite but the area of coverage became smaller as the apogee became progressively lower.[8] Coverage at perigee, which changed very little during the life of the satellite, was limited to the smaller areas outlined by the dotted lines.

From one to five of the ground stations could receive the LOFTI I telemetry signals as the satellite passed over the North and South American regions. Reception by these stations overlapped on some passes, providing occasional redundancy of data. Six of the telemetry stations were each equipped with a 10-foot square loop antenna and VLF receiver for direct reception of 18-kc signals. This facility made possible comparison of the telemetered VLF signals with VLF signals which had arrived at these stations via the usual terrestrial paths.

Signals Received from NBA

As the satellite came within their range during its first revolution around the Earth, the North American field stations began reporting good telemetered VLF signals. The South American station tapes subsequently received also showed good VLF signal reception and the tapes received from Australia showed that NBA signals were reaching the satellite more than 10,000 miles away.

Figs. 7 and 8 are twelve-second samples of LOFTI data as recorded at the NRL satellite research station at Stump Neck, Maryland. In Fig. 7, the time is 35 minutes after midnight EST on February 23, 1961. The satellite was then in its 16th revolution around the earth, 550 km (340 statute miles) high and north-northeast of the transmitter at a ground distance of nearly 1600 km (1000 miles).

The upper trace (telemetry subchannel IRIG[9] band 4), shows a section of the keying envelope of the NBA signal as it appeared in the detector output[10] of LOFTI's loop receiver. The detector output of the whip receiver and that of the loop receiver time-shared IRIG band 4. The parts of the trace labeled "marker" are intervals in which the subcarrier frequency was shifted in the satellite to either the upper or the lower limit of band 4 to indicate that loop receiver or whip receiver output, respectively, would follow. Since the whips were not extended, the detector output of the whip receiver contained little or no desired signal information. For this reason, only a few seconds of the whip receiver record are shown.

The envelope of eight of NBA's time ticks (one pulse per second, each 0.3 second long) follows after the loop marker interval in the upper trace of Fig. 7. The sharp downward spikes appearing in the marker interval and at the tops of the time pulse envelopes are indicative of disturbances in telemetry reception rather than field strength variation of the NBA signal at the satellite. Satellite VLF receiver output saturation level is exceeded part of the time in this sequence, indicating that the magnetic field of the NBA signal at the satellite was equivalent in intensity to the magnetic field associated

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[8] See Appendix II.

[9] Inter-Range Instrumentation Group Standards were used in assignment of subcarrier frequency bands (see Appendix III).

[10] An envelope detector channel branched out from the first intermediate frequency (IF) amplifier system of each VLF receiver. Its input (first IF) bandwidth was 28 cps at 3 db down and its output (RC filter) cutoff was about 30 cps.

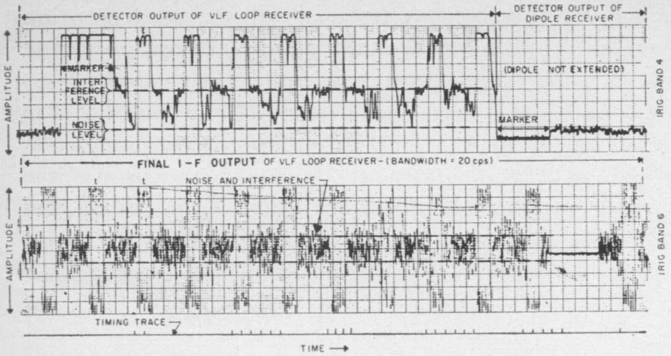

Fig. 7—Typical signal output of LOFTI I loop receiver (detector and final IF amplifier). Orbit revolution 16, February 23, 1961, 12:35:38 to 12:35:50 A.M. EST. Satellite over Caribbean area; height, approximately 550 km; ground range from VLF transmitter (NBA, Panama), approximately 1600 km, north-northeast.

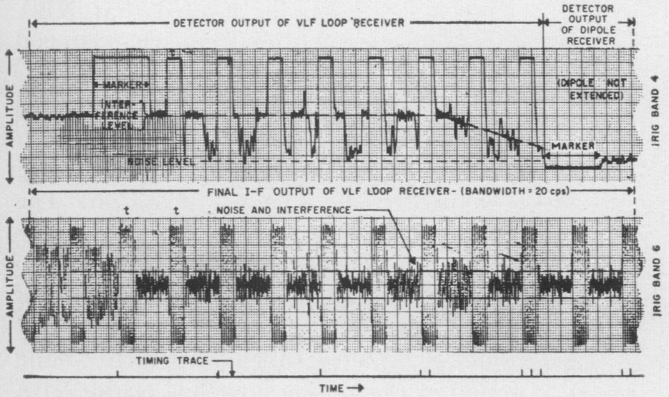

Fig. 8—Signal output of LOFTI I loop receiver under better telemetry conditions. Orbit revolution 29, February 23, 1961, 9:10:33 to 9:10:45 P.M. EST. Satellite over Gulf of Mexico; height, approximately 200 km; ground range from VLF transmitter (NBA, Panama), approximately 2500 km, north-northeast.

with an electric field intensity of at least 100 μv/m[11] in free space.

Interference generated by TRANSIT's electronic system is evident in the intervals between the time ticks. While obscuring the desired signal only partially in this case, it is evident that TRANSIT interference could be expected to make determination of signal intensity from the telemetry records difficult when the VLF signals are weak.

The lower trace in Fig. 7 shows the second (final) IF amplifier output of LOFTI's loop receiver (25 cps center frequency, 20 cps bandwidth at 3 db down). The receivers were designed to compress an input signal range of 40 db into an output signal range of 20 db. Corrected for this compression, the NBA signal to ambient noise ratio (in a 20-cps band and excluding TRANSIT interference) is 46 db for the eight-second period shown.

Fig. 8 is similar to Fig. 7 but was recorded during orbit revolution number 29, 10 minutes after 9 P.M. EST on February 23, 1961. The satellite is lower, at about 190 km (120 miles) altitude, and farther from the transmitter (about 1500 miles north-northeast). The signal and interference waveforms are more clearly defined due, most likely, to better telemetry reception. However, the corrected signal-to-noise ratio (SNR) is the same (46 db). The signal level in Fig. 7 is somewhat greater, which likely is indicative of different ionospheric conditions. It is also possible that the satellite loop was oriented for more nearly optimum response in that case.

SIGNALS RECEIVED FROM NPG

During the middle of March 1961, Naval Radio Station NPG (Jim Creek, near Seattle, Washington) transmitted signals at 18 kc for LOFTI I. The radiated power of the transmitter was 200 to 250 kw. A special keyer produced the keying waveform shown in the lower trace of Fig. 9. This is a 45-second sample of the signal as it appeared March 14, 1961, about 37 minutes after midnight EST, in the detector output of the ground VLF receiver at Stump Neck.

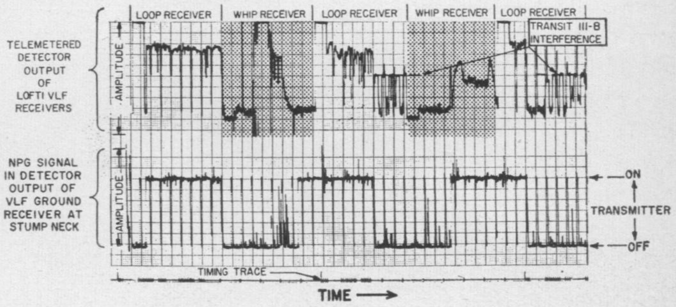

Fig. 9—Reception from transmitter to north of satellite; LOFTI I loop and whip receiver detector output compared to detector output of Stump Neck VLF ground receiver. Orbit revolution 313, March 14, 1961, 12:37:20 to 12:38:05 A.M. EST. Satellite over Florida; height, approximately 767 km; ground range from transmitter (NPG, State of Washington), approximately 4000 km, east-southeast.

The keyer switched NPG's carrier wave alternately on and off for 7½ seconds each interval. During the "on" time, it interrupted the carrier briefly at 1-second intervals, resulting in the downward spikes seen one second apart in the graph. Similarly, the keyer switched the carrier on briefly seven times in each "transmitter-off" period. This keying pattern could be easily identified in the presence of noise and interference.

The upper trace shows the signal as it appeared in the detector output of the LOFTI I receivers. The satellite was moving in its 313th orbital revolution and at that time (12:37 P.M. EST) was approximately 3850 km (2400 miles) east-southeast of NPG (ground range) and about 767 km (475 miles) high. The keying spikes seen in the output of the ground receiver also appear (at a slightly later time) in the output of the satellite's loop receiver. Except for TRANSIT interference at the satellite, the SNR at the satellite and the ground installation do not differ greatly. TRANSIT interference is very evident in two of the three loop sections of the record; however, NPG's signal is clearly evident through the interference.

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[11] Electric field intensity at the loop center at which the loop receiving system of the satellite reached output saturation in calibration measurements made on the ground.

Signals Received from NBA over Australia

Fig. 10 is a 23-second section of telemetry record from the telemetry station in Australia. It shows the final IF amplifier output of LOFTI's loop receiver during orbit number 130 (March 2, 1961) as the satellite passed over Australia at a height of 725 km (450 miles). LOFTI's ground range to the transmitter at Panama was then close to 16,800 km (10,400 miles). The time was close to 3:30 A.M. Australian standard time (night) at the satellite (about 2:30 P.M. EST (day) at NBA). The NBA keying waveform has been sketched in below the record as an aid to recognition of the one-second time pulses. Although the mean SNR at the loop is estimated as approximately 10 db in this sequence, large cycle-to-cycle variations are apparent in the IF output wave, indicating that rapid fluctuations of signal and noise field intensity have been encountered as the satellite raced along its path.

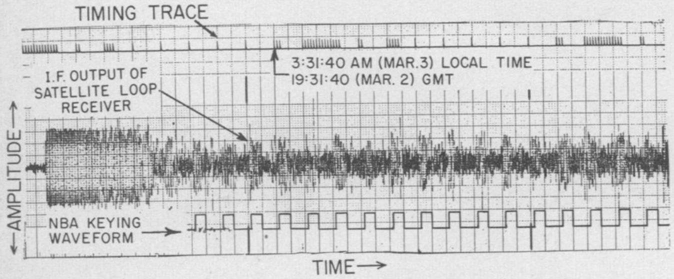

Fig. 10—Reception 10,400 miles from VLF transmitter; output of LOFTI I loop receiver (final IF amplifier). Orbit revolution 130, March 2, 1961, 3:31:32 to 3:31:54 A.M. Australian Standard Time. Satellite over Australian area; height, approximately 725 km; ground range from transmitter (NBA, Panama), approximately 16,775 km, west by southwest.

VLF Signal Echoes in the Ionosphere

Fig. 11 shows the final IF amplifier output of the satellite loop receiver as recorded shortly before 7 A.M., EST (about dawn) on March 22, 1961, during orbit number 434. The satellite was approximately 385 km (240 miles) high and at about 2100 km (1300 miles) ground range north of NBA. The envelope of the NBA time pulses as seen in the detector output of the telemetry station's VLF ground receiver appears directly below the satellite IF output trace. A strong echo (marked E) can be seen in the output of the satellite receiver about two thirds of a second after the onset of the first time pulse T_1. A similar echo appears following each time pulse T_2 through T_9 except for the period between E_2 and E_5, which is obscured by noise. A smaller echo, marked $2E_5$, may be the result of a second cycle of reflection of the time pulse (T_5) transmitted about one and a third seconds earlier.

The echoes are probably the result of whistler-path signal propagation. Attenuation in this mode is not very great, as is indicated by the small differences in amplitude of the echoes as compared to the directly received pulses. The most likely path for the VLF wave in this mode is southward along the contour of the geomagnetic field, then back north in the same fashion after reflection and change of polarization at the upper face of the ionosphere south of the geomagnetic equator. However, traversal of the full length of a geomagnetic line at free-space propagation velocity, even from as far north of NBA as 40° geometric latitude, would account for only a small fraction of the time delay of the echoes. Most of the delay must be the result of slower propagation velocity of the VLF wave, an effect to be expected in the ionized medium.

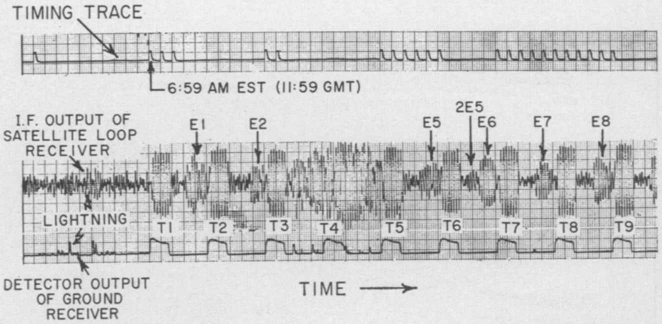

Fig. 11—VLF echoes in the ionosphere. Signal output of LOFTI I loop receiver (final IF amplifier). Orbit revolution 434, March 22, 1961, 6:58:58 to 6:59:08 A.M. EST. Satellite off east coast of Florida; height, approximately 385 km; ground range from transmitter (NBA, Panama), approximately 2100 km north. T_1 to T_8 are time pulses of NBA as received by the satellite, E_1 to E_8 are primary echoes of these pulses and 2E5 is probably a secondary echo.

Sferics in the Ionosphere

The random short-duration pulses preceding the first time pulse of the ground receiver trace in Fig. 11 are identified on the tape record as "lightning." Considerable noise appears in the IF output of the satellite loop receiver at the same time. About 3 seconds (and 14 miles) later, another, much larger, noise burst at the satellite largely obliterates signals in the vicinity of the fourth time pulse, even though the ground station trace here shows less noise than associated with lightning in the previous burst. It appears likely that the source of the second burst was much closer to the satellite.

Signal and Noise During a Daylight Pass

Fig. 12 shows the *apparent* electric field intensity[12] (and the corresponding magnetic field intensity) of the NBA signal and of the ambient noise level as indicated by LOFTI's loop receiver output during a 6400 km long (4000 mile) daylight pass (March 21, 1961, orbit number 421). The principal sources of TRANSIT interference were silent. Over 800 data points provided the second-by-second outline of each of the three curves, which respectively define the quasi-maximum apparent signal intensity (upper level), the quasi-minimum apparent signal intensity (lower level) and the quasi-peak apparent intensity of ambient noise at the satellite (dotted curve). The curved abscissa at the one microvolt-per-meter level of the ordinate defines the ground track of the satellite on the earth's surface as it moves in the ionosphere from out over the Pacific Ocean into the Atlantic region.

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[12] The electric field intensity (microvolts per meter) which produced the same output from LOFTI's loop receiving system when the satellite was on the ground as was subsequently observed by telemetry when the satellite was in orbit. The ratio of electric field intensity in the ionosphere to that in free space for the same power level is a function of the ratio of the wave impedances in the two media. The loop antenna responds only to change of magnetic flux ($d\phi/dt$) in either medium. The magnetic field intensity (microampere-turns per meter) may be determined for each medium by dividing the apparent microvolts per meter values by the impedance of free space (377 ohms). However, the relative power level of the signals in the two media cannot be calculated until measurements of wave impedance in the ionosphere have been made.

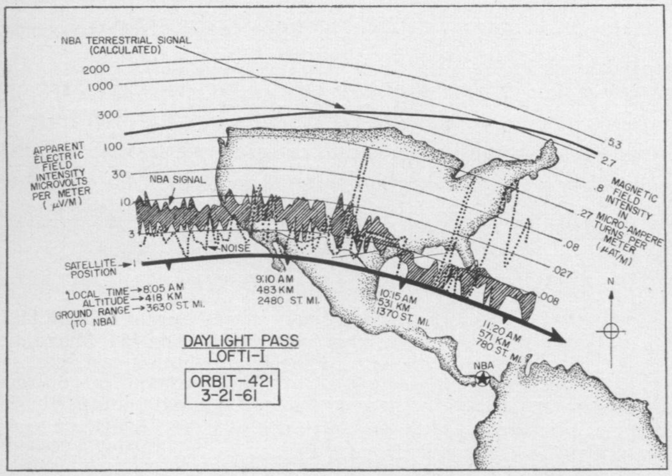

Fig. 12—VLF signal and noise field intensity at the satellite during 17 minutes of a forenoon pass. Upper boundary of signal trace is second-to-second quasi-maximum level; lower boundary is quasi-minimum level. Noise values are quasi-peak levels.

Local mean sun time is marked at the five minute elapsed time points along the track. The satellite is moving in daylight all the way, approaching high noon at the eastern end of the pass. Its altitude increases from 420 km (260 miles) at the west end to 565 km (350 miles) at the east end. At the same time, its ground range to the transmitter decreases from over 5800 km (3600 miles) at the first time marker to less than 1300 km (800 miles) at the last marker.

The field intensity of NBA's signal on the terrestrial surface directly under the satellite, as computed from a modified form of the Baldwin-McDowell equation, is shown by the smooth curve in the upper part of the graph. At the western end of the pass, the ratio of the apparent electric field intensity of the NBA signal at the satellite to the NBA computed electric field intensity at the Earth's surface is about −26 db (±5 db). At this point, the atmosphere is in a state of ionization corresponding to about two hours of solar irradiation. At the eastern end of the pass, the ionization is approaching the noon values; here the ratio is about −55 db (±5 db).

The quasi-peak noise level is below the signal level by roughly 6 to 12 db during most of the transcontinental part of this pass. Occasional large increases of noise appear in the data but persist for only a few seconds. However, beyond the Gulf of Mexico, over the Caribbean area, the noise level is much higher than the NBA signal level much of the time.

SIGNAL AND NOISE DURING A DAWN PASS

Fig. 13 is a presentation of the same type as Fig. 12 but for a dawn[13] pass (March 22, 1961, orbit number 434). The apparent signal level at the satellite relative to the computed terrestrial surface value drops rapidly as LOFTI and its companions move from the west toward sunrise at the satellite (from about −26 db ±5 db to about −46 db ±5 db). Immediately after it passes the sunrise line, the satellite moves into a region of rapidly increasing VLF field intensity. Loop receiver saturation level (indicating signals of over 100 μv/m apparent electric field intensity) is reached in about two minutes elapsed time. The apparent electric field intensity is then less than 15 db below the computed surface value; the satellite is at a position corresponding to about six hours before noon. From there on, the signal decreases with further satellite motion to the east, reaching a relative value of about −40 db ±5 db at the end of the pass. The position then corresponds to about four hours before noon.

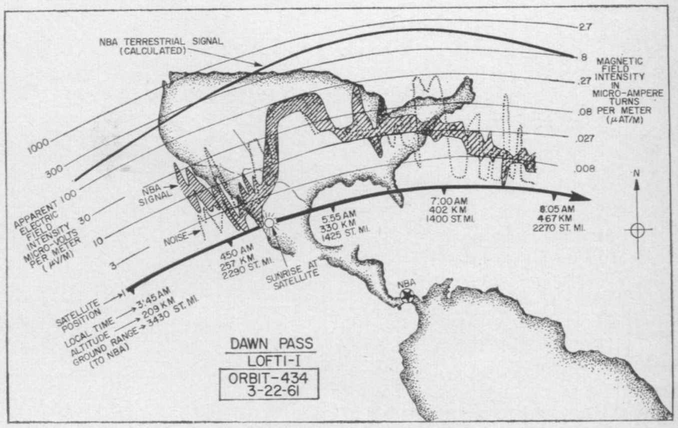

Fig. 13—VLF signal and noise field intensity at the satellite during 15 minutes of a dawn pass.

The ambient noise level is higher throughout most of this pass than in the daylight pass of Fig. 12, exceeding the signal level very considerably shortly before and after the satellite passes the sunrise position. Again the noise level exceeds the NBA signal level much of the time over the Caribbean area.

EFFECT OF DIRECTION OF SATELLITE FROM TRANSMITTER

Comparison of NPG signal data to NBA signal data affords some experimental confirmation of the effect of difference in angle θ of the wave normal relative to the geomagnetic field on attenuation. NPG is about 40° farther north than NBA. Limited data available for a period when the two stations were operating simultaneously at 18 kc indicates that the NPG signal in the ionosphere was attenuated relative to its computed ground signal intensity roughly 10 db less than NBA's signal.

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[13] Similar data for night and dusk passes were not yet available at the time of this writing.

The computed effect of θ on power loss through the model ionosphere of Fig. 2 is shown below.

Angle θ Between Wave Normal and Geomagnetic Field	Computed Transmission Loss Through Ionosphere	
	Night	*Day*
0° (or 180°)	2.0 db	27 db
30 (or 150°)	3.5	33
60 (or 120°)	15	75
90	>100,000	>100,000

TIME DISTRIBUTION OF SIGNAL INTENSITY

The time distribution of the apparent field intensity of the NBA signals observed by LOFTI in a particular portion or volume of the atmosphere is shown in Fig. 14 relative to computed ground signal intensity. To develop the data in this form, the second-by-second values for a number of passes of the satellite through this volume were reduced to one-minute mean values.[14]

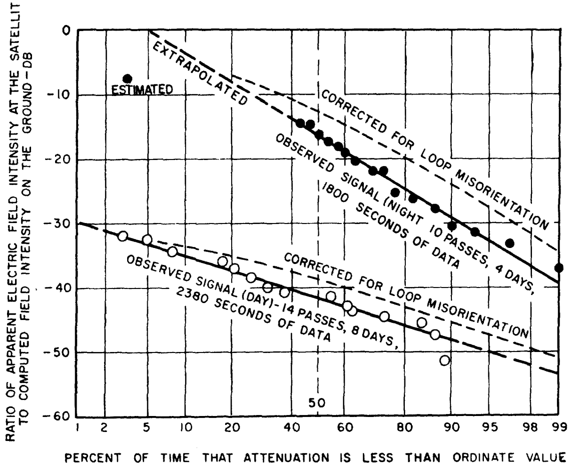

Fig. 14—Cumulative time distribution of NBA signal intensity at the satellite in a space to the north of NBA approximately 4400 km long (west to east) by 890 km wide (north to south) by 555 km high, and 165 km above the terrestrial surface at closest approach. Satellite at extreme line-of-sight distance from transmitter most of the time.

The volume to which the distribution curves of Fig. 14 apply was to the north of station NBA and extended from 20 to 28° N latitude and 60° to 100° W longitude. The satellite was at altitudes between 380 and 720 km (225 and 445 statute miles) during the daytime passes and between 165 and 360 km (105 and 224 miles) during the night-time passes. The particular passes and this volume were chosen because the greatest amount of reduced data for transmitter to satellite distances close to the extreme line-of-sight range was available for them, as of this writing.

The night curve in Fig. 14 presents data from 10 passes over a period of four days. Altogether, these passes provided 1800 seconds of telemetered information. Essentially all of the NBA pulses are visible in the telemetry recordings of these passes, except for a few moments when noise bursts obscured the signals briefly or when telemetry reception failed momentarily. Similarly, the day curve is derived from 14 passes on 8 days that together provide 2380 seconds of data. About 10 per cent of the time ticks are completely masked by VLF noise in these recordings. The designation "night" as applied in Fig. 14 is the interval of one and a half hours after sunset to one and a half hours before sunrise. Likewise, "day" is the period from one and a half hours after sunrise to one and a half hours before sunset.

The one-minute mean data points for both day and night cluster along lines of log-normal distribution. The night curve has no data points below 15-db attenuation because the loop receiver reached output saturation when the ionospheric attenuation was less than this value. The one point shown at about 8 db (marked "estimated") was derived from observations of output signal magnitude during periods when the 40-db pad was inserted in the satellite's loop circuit. It is not considered to be as accurate as the rest of the data and the night curve has therefore been extended by straight line extrapolation. The lines marked "corrected for loop misorientation" represent the observed data compensated, on a probability basis, for the lower loop output resulting from the likely misalignment of the loop relative to the VLF wave front.[15]

DISCUSSION OF DISTRIBUTION CURVES

The range of amplitude variation of the observed night signal in the 3 to 99 per cent time range, including the estimated point at 8-db attenuation, is about 30 db. The 3 to 99 per cent range for the observed day signal (including the extrapolated section from 90 to 99 per cent) is about 21 db. These values compare fairly well with the range of fading observed in long-distance VLF ground signal propagation studies.

The difference in attenuation between the day and night curves at the 50 per cent time points is about 26 db. This is nearly the same as the difference between the computed day and night absorption loss (cumulative attenuation) above 160 km (100 miles) altitude in the model ionosphere (Fig. 4).

The attenuation of magnetic field intensity of the VLF radio wave is indicated directly by the ordinate in Fig. 14. It appears that 50 per cent of the time the magnetic field intensity of the signal in the ionosphere at night is 13 db less than the computed ground field and is 38 db less during the daylight period. These figures apply to the particular conditions under which the data was taken and include correction for probable loop misorientation.

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[14] In general, the field intensity at the satellite loop, as gauged from final IF output level telemetered from the satellite, did not vary much more than about three to one in any one minute interval. Each minute of data was examined second by second and a microvolt-per-meter level was assigned to it which represented a best estimate of the mean level for that one minute interval. Although the satellite loop receiver saturated at 100 μv/m, programmed 2-second intervals of reduction of loop signal input to the receiver occurred once each 30 seconds. During this time, a 40-db attenuator was automatically inserted into the loop circuit by the satellite instrumentation. The resulting increase of input required to produce receiver saturation has made possible a rough estimate of the field intensity causing the saturated condition immediately prior to and succeeding these 2-second intervals.

[15] See Appendix IV.

Since the interface entry and the subsequent absorption losses are both dependent to some degree on the angle between the wave-normal and the geomagnetic field, becoming less as θ approaches 0 degrees, the attenuation of the signal by the ionosphere should, in general, be less at the higher latitudes.

TIME DELAY AND DOPPLER SHIFT

The low velocity of VLF wave propagation in the ionosphere indicated by the long delay time of the echoes in Fig. 11 is also apparent in the relatively much longer time required for the signal to arrive at the satellite as compared to arrival time at the ground VLF receivers. Time pulse delays ranging from about 10 to 200 msec appear throughout the data. As much as 8 cps Doppler shift of NBA's carrier frequency, which is held constant at the transmitter to 1 part in 10^{10} (about $\pm 2 \times 10^{-6}$ cps), appears in the data so far examined.

EFFECT OF ALTITUDE

As of this writing, about one sixth of the LOFTI I data has been reduced. No correlation between altitude of the satellite and the apparent signal intensity has yet become evident. The data so far studied does not disagree with the concept that the absorption loss occurs almost entirely in the D region.

CONCLUSIONS

General conclusions which are derived before all the significant data from an experiment has been reduced and analyzed are necessarily tentative. However, the LOFTI I data and studies do indicate that:

1) A considerable portion of the energy radiated by transmitters and other sources of VLF signals in the lower atmosphere penetrates the interface between the ionosphere and lower atmosphere and appears within the ionosphere. It seems likely that there is a transition loss at the interface, after which the signal energy is further reduced by attenuation due to absorption plus some spreading loss as the wave moves upward through the ionized air.

2) Most of the propagation loss between the ground transmitter and satellite receiver appears to occur below 100 km altitude.

3) The signal intensity data so far reduced to statistical form indicates that 50 per cent of the time the magnetic field intensity of the VLF wave is reduced less than 13 db at night and less than 38 db by day because of passage through the ionosphere. The corresponding figures for 10 per cent and 90 per cent of the time are 4 db and 29 db at night, and 33 and 45 db by day. This information is, however, based on only about 2000 seconds of data each for the night and day conditions, and applies only to 18-kc signals received by the satellite at latitudes less than 28° north and to the north of the transmitter.

4) The VLF signal appears to travel to its point of reception in the ionosphere much more slowly than in free space. Transmission delay as great as thirty times the free space delay appears in the data.

5) The echoes of station NBA signals observed in the experiment lend support to present theories of whistler propagation.

6) Satellite communication using VLF radio waves is feasible and affords some interesting possibilities for future application.

FUTURE PLANS

Further LOFTI experiments are planned for exploration of VLF reception at the higher latitudes and at other frequencies. Transmission from within the ionosphere is to be studied. It is expected that, in addition to other data, the next experiment will provide the information on electric dipole impedance in the ionized medium lost in the LOFTI I experiment.

APPENDIX I

ATTENUATION OF A RADIO WAVE PROPAGATING IN A MAGNETO-IONIC MEDIUM

The absorption coefficient χ for an electromagnetic wave in a magneto-ionic medium can be determined from the complex refractive index n.

$$n^2 = (\mu - i\chi)^2 = 1 - \frac{X}{1 - iZ - (1/2)Y_T^2/(1 - X - iZ) \pm \left[\frac{1}{4}Y_T^4/(1 - X - iZ)^2 + Y_L^2\right]^{\frac{1}{2}}} \qquad (2)^{16}$$

where

$\mu =$ refractive index,
$X = \omega_N^2/\omega^2$,
$Y_L = \omega_L/\omega$,
$Y_T = \omega_T/\omega$, and
$Z = \nu/\omega$.

The quantities

$\omega_N^2 = 4\pi N e^2/\epsilon_0 m$,
$\omega_L = \omega_H \cos\theta = (\mu_0 H_0 e/m) \cos\theta$,
$\omega_T = \omega_H \sin\theta = (\mu_0 H_0 e/m) \sin\theta$,
$\nu =$ collision frequency, and
$\omega =$ wave angular frequency;

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[16] J. A. Ratcliffe, "The Magneto-Ionic Theory and Its Application to the Ionosphere," Cambridge University Press, New York, N. Y., and London, Eng.; 1959.

in which

ω_N = plasma angular frequency,
ω_H = gyro angular frequency,
N = electron density,
H_0 = magnitude of the imposed magnetic field,
θ = angle between the direction of the magnetic field and the wave normal,
e = charge of the electron,
m = mass of the electron,
μ_0 = magnetic permittivity of free space,
ϵ_0 = electric permittivity of free space.

An expression for α, the power attenuation of the radio wave per unit distance in the ionosphere, may be derived from χ in equation (I-1). A greatly simplified form of this expression appears as (1).

APPENDIX II

VARIATION OF ORBITAL PARAMETERS

Orbit Attained

Certain major orbital parameters of LOFTI I and its attached companions four days after launch are given in Table I. This data was developed from Minitrack station observations by the NASA Computing Center and issued by the Goddard Space Flight Center.

TABLE I

MAJOR ORBITAL ELEMENTS OF SATELLITE 1961 ETA FOR THE EPOCH 0353 UT (10:53 PM, EST), FEBRUARY 25, 1961

Anomalistic Period (Time for one revolution around Earth, perigee to perigee)	95.92030	Minutes
Inclination (Plane of orbit relative to Earth's equatorial plane)	28.37	Degrees
Argument of Perigee (Angle between ascending node and perigee in plane of orbit)	60.392	Degrees
/Motion Plus (Progression of perigee)	10.676	Degrees per day
Eccentricity (Departure of orbit from perfect circle)	0.05731	
Semi-Major Axis (Half-length of major axis)	1.08826	Earth Radii
Perigee [Least altitude relative to equatorial radius of earth (=3963.3 statute miles)]	103	Statute Miles
Apogee (Greatest altitude relative to equatorial radius of earth)	597	Statute Miles
Velocity at Perigee	17,953	Miles per hour
Velocity at Apogee	16,007	Miles per hour

Progression of the Apogee

Although 1961 Eta's perigee became lower by only a few miles during its short life, its apogee progressively fell from almost 600 miles to nearly 250 miles, as shown in the upper part of Fig. 15.

Table I gives the rate of progression of the perigee as very nearly $10\frac{2}{3}$ degrees per day at that particular epoch in time. This rate did not change greatly during the nearly $36\frac{1}{3}$ days of the satellite's life and the apogee progressed similarly. The change in sub-orbital position[17] of the apogee is shown in the lower part of Fig. 15.

The progression in position of the apogee and perigee over a complete cycle in latitude allowed LOFTI I to sample the VLF field at varying altitude over all the areas covered by telemetry before 1961 Eta perished, presumably in a burst of fire, on March 30, 1961.

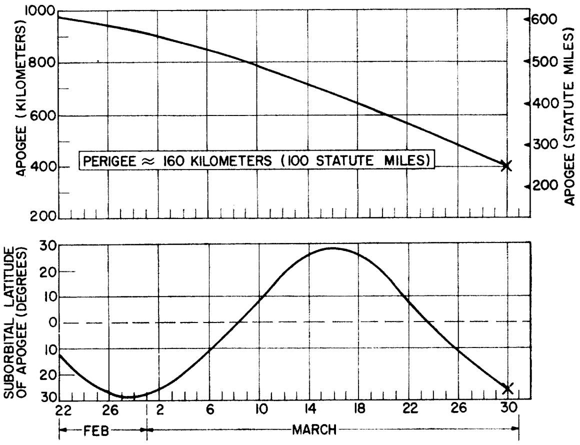

Fig. 15—Reduction in altitude of the apogee and variation of the apogee in latitude during the lifetime of the satellite. The altitude of the perigee remained close to 160 km until the end of life.

APPENDIX III

SATELLITE INSTRUMENTATION[18]

The Satellite

LOFTI I (Fig. 16) was a 20-inch diameter sphere that weighed 57 pounds complete with instrumentation. A loop antenna of approximately elliptical shape, which had a mean diameter of 20 inches, was mounted on the sphere. The satellite's two 15-foot long whip antennas were wound in strip form on separate motor-driven reels inside the sphere. The strips were to be unreeled upon radio command, assuming a hollow-rod form as they extended slowly through the upper guide tube and an orifice in the base of the sphere, respectively.[19] Six sets of solar cells assembled in patches on the surface of the sphere provided primary power for the electrical and electronic equipment. Eight photo-electric sensors were mounted on the sphere, four to provide data on satellite attitude relative to the sun and four to provide similar information on attitude relative to the Earth. Four rods, which were folded up during launch, were the radiator elements of a turnstile antenna for the 136-Mc telemetry system.

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[17] Point on Earth's surface vertically under the satellite.

[18] The Radio Techniques Branch, Radio Div., USNRL, planned and directed the experiment, and provided the satellite VLF and ground station instrumentation. The Satellite Techniques Branch, Applications Res. Div., USNRL (M. Votaw, Branch Head) provided the satellite, including the VHF instrumentation, and was responsible for launch.

[19] H. R. Warren, "DeHavilland antenna erection unit," *Proc. of Fifth National Convention on Military Electronics*, Washington, D. C.; June 26–28, 1961.

Electronic Instrumentation

The block diagram (Fig. 17) shows the major electronic elements of LOFTI I. The telemetered information was carried by frequency variation of subcarriers in Inter-Range Instrumentation Group (IRIG) frequency bands 3 to 7 (inclusive), which amplitude-modulated the carrier of the 136.17-Mc telemetry transmitter. The divided-down (1057 cps) output of the individual sync-locked crystal oscillators of the two VLF receivers also amplitude-modulated the telemetry carrier, one of the 1057 cps outputs being considerably attenuated relative to the other to permit recognition in the telemetry in case of loss of synchronization. The term "25 cps IF output" in the diagram refers to the output of the final stage of the second (25 cps) IF amplifier of the VLF receiver, and the term "detected output" refers to the output of the diode detector following the first IF (1082 cps) amplifier.

Pickaback Mounting

Fig. 18 shows LOFTI I as it appeared mounted as a copassenger on the TRANSIT III-B satellite. The two-satellite assembly was attached to the second stage of the Thor/Able-Star launch vehicle and covered by a nose cone during launch.

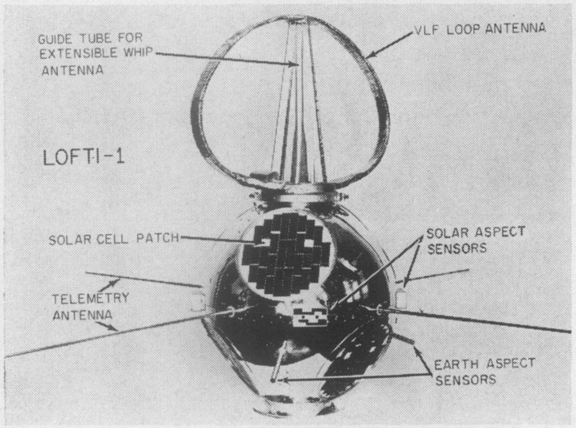

Fig. 16—Side view of the LOFTI I satellite.

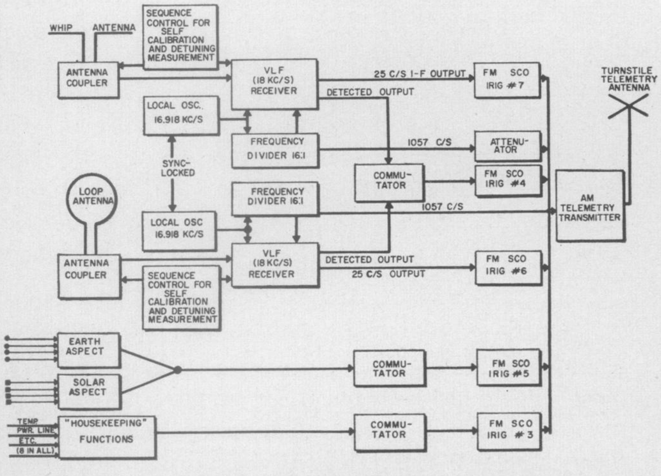

Fig. 17—Major electronic elements of LOFTI I satellite instrumentation which pertained to the VLF experiment.

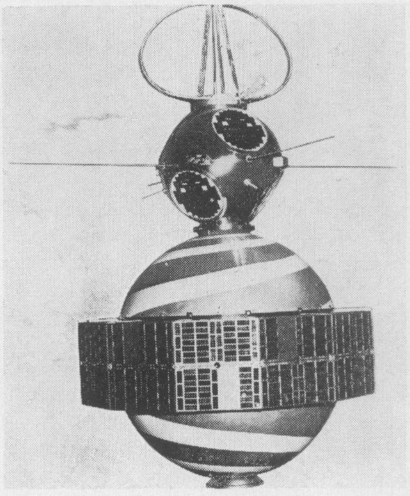

Fig. 18—Side view of LOFTI I mounted on TRANSIT III-B.

APPENDIX IV

DECREASE IN OUTPUT OF A SINGLE PLANE LOOP DUE TO MISORIENTATION RELATIVE TO THE WAVE NORMAL

Assuming circular polarization of the VLF wave in the ionosphere, the LOFTI loop would exhibit cosine-law response when rotated about any axis perpendicular to the wave normal. The loss due to misorientation would then be:

Misorientation (Per cent of 90°)	Corresponding Reduction in Loop Output Voltage
0 per cent	0 db
20	0.5
30	1
40	1.5
50	3
60	4.5
70	7
80	10
90	16
95	22
99	36

ACKNOWLEDGMENT

The LOFTI I program has been sponsored by the Special Projects Office through the Bureau of Ships and conducted by the Radio Division of the U. S. Naval Research Laboratory with the cooperation of the Applications Research Division. A major effort of this nature is very much dependent on the devotion, knowledge, and skill of many persons; unfortunately it is impractical to name them here, but the authors are deeply grateful to them all. The generous and expert cooperation of the National Aeronautics and Space Administration and its personnel is gratefully acknowledged. Discussions with R. A. Helliwell and L. H. Rorden of Stanford University and the Stanford Research Institute, respectively, have been very helpful in LOFTI planning.